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$^{230}Th/^{234}U$ ages of calcite cements of the proglacial valley fills of Gamperdona and Bürs (Riss ice age, Vorarlberg, Austria): geological implications

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Abstract

In the lower reaches of two tributary valleys of the Ill valley (Vorarlberg, Austria), thick successions of pebbly alluvium that accumulated upon blocking of the valleys in association with the advancing Ill glacier were minimum-dated, for the first time, by the thorium-uranium method to the Riss Glacial. Previous age assignments by other authors ranged from the Mindel-Riss Interglacial to the early Würmian.

Both dated successions are situated in the lower reach of left-hand tributary valleys to the Ill valley, a major intra-Alpine valley shaped largely by Pleistocene glaciers. The more northern tributary valley (Gamperdona valley) contains a succession a few hundreds of meters thick of stacked, bottomset-to-topset packages of Gilbert-type deltas that prograded into proglacial lakes. The southern tributary (Brandner valley), in turn, contains a succession mainly of subhorizontally-bedded coarse-grained fluvial conglomerates. The conglomerate successions of both valleys are incised by a fluvial bedrock gorge. Thorium-uranium dating of calcite cements yielded a probable cementation age of 129 ± 6.5 ka for the sample from Gamperdona valley ("lower conglomerate unit"), and a cementation age of 128 ± 10 ka for the sample of Bürser Konglomerat.

This suggests that each succession accumulated during the immediately preceeding Riss Glacial, as a result of blocking of the fluvially-shaped (V-shaped) lower reaches of the tributary valleys during advance of the Ill glacier along the trunk valley. The radiometric age data indicate that at least the lower reaches of both tributary valleys, onlapped by fluviatile deposits and proglacial lake successions, were largely shaped before the Riss ice age. The bedrock gorges cut into both conglomerate successions may have incised, in part at least, during the Riss-Würm interglacial, and became further shaped mainly during the Late-Glacial to Holocene.

Mächtige Abfolgen fluviatiler Konglomerate, die entlang des Unterlaufs zweier Seitentäler des Ill-Tales (Vorarlberg, Österreich) aufgeschlossen sind, konnten mittels der Thorium-Uran Methode erstmals in das Riss-Glazial mindest-datiert werden. Die Abfolgen gelangten während eines Vorstoßes des Ill-Gletschers zur Ablagerung, als Folge des Verschlusses beider Seitentäler durch den Gletscher im Ill-Tal. Die Abschätzungen früherer Autoren zum Alter dieser Folgen reichen vom Mindel-Riss Interglazial bis zum frühen Würm.

Beide Abfolgen liegen entlang des Unterlaufes zweier orographisch linker Seitentäler des Ill-Tales, einem großen inneralpinen Tal, das hauptsächlich durch pleistozäne Gletscher geformt wurde. Das nördlichere der beiden Seitentäler, das Gamperdona-Tal, enthält eine mehrere hundert Meter mächtige Abfolge hauptsächlich aus gestapelten bottomset-to-topset Paketen von Gilbert-Typ Delten, die in proglaziale Seen vorbauten. Das südlichere Seitental (Brandner-Tal) hingegen beinhaltet eine Folge hauptsächlich aus subhorizontal gebankten, grobkörnigen fluviatilen Konglomeraten. Die Konglomerat-Abfolgen beider Täler sind durch je eine Klamm mit Gesteinskanal (bedrock channel) durchschnitten. Thorium-Uran Datierung von Kalzitzementen ergab ein wahrscheinliches Zementationsalter von 129 ± 6.5 ka für die Probe aus dem Gamperdonatal ("untere Konglomerat-Einheit") und ein Zementationsalter von 128 ± 10 ka für die Probe aus dem Bürser Konglomerat.

Dies legt nahe, dass beide Abfolgen während des unmittelbar vorangegangenen Riss-Glazials zur Ablagerung gelangten, wahr scheinlich infolge der Absperrung der fluviatil geformten (V-förmigen) unteren Läufe der Seitentäler während eines Vorstoßes des Ill-Gletschers. Zumindest jene Teile des Unterlaufes beider Seitentäler, die von den fluviatilen Konglomeraten und auch von Eisrandsee-Sedimenten angelagert werden, wurden daher vor dem Riss-Glazial geformt. Die Klamm, die in jede der Konglomeratabfolgen einge schnitten ist, bildete sich zumindest zum Teil wahrscheinlich bereits im Riss-Würm Interglazial und wurde hauptsächlich während des Spät-Glazial bis Holozän weiter geformt.

1. Introduction

Apart from glacially-shaped valleys, steep-flanked fluvially-cut valleys and gorges are among the most characteristic geomorphic elements of mountain belts (Summerfield, 1991). At least for the Eastern Alps, however, the potential ages and rates of valley cutting are poorly constrained. There exists a gap in documentation between records of latest Paleogene to Miocene onset of incision of major valleys, such as the Inn valley (cf. Frisch et al., 2000; Ortner & Stingl, 2001), and Quaternary valley incision and relief development. For many inner-Alpine valleys and gorges, physical stratigraphy and cross-cutting relations traditionally used to constrain the relative age of deposits and landforms can hardly be applied. In the Alps, in contrast to a widespread assumption that gorges are commonly of post-Würmian age, in a few cases it can be demonstrated by physical stratigraphy and/or by absolute age-dating that they are older in origin (Tricart, 1960; de Graaff, 1997, Wischounig, 2006). Because of the typically patchy preservation of Quaternary deposits in the Alps, however, age assignments were notoriously difficult before methods of absolute age-dating became increasingly available, and at many locations still are.

In Vorarlberg (Austria), in the lower reaches of the Gamperdona valley and of the adjacent Brandner valley, successions up to hundreds of meters thick are present that consist mainly of proglacial pebbly alluvium (Fig. 1) (de Graaff, 1996). The only relative age control is given by the superposition of the successions by till of the Last Glacial Maximum (LGM), but the age assigned to the conglomerates always was highly controversial. According to Ampferer (1908), the conglomerates accumulated during the Würm, but well-before the LGM (in present-day terminology). Conversely, Heissel (1960) argued for a Riss-Würm interglacial position of the conglomerates whereas later, Heissel et al. (1965) favoured a Mindel-Riss interglacial age. Hantke (1970), by contrast, considered an early Würmian age as the most probable. Finally, based on detailed mapping, de Graaff (1996, 1997) suggested that the sedimentary successions accumulated during the Riss ice age. Such an uncertainty in age assignment relates to the fact that many Alpine Quaternary deposits such as glacial tills, lithified talus breccias and pebbly alluvium in most cases do not contain "conventional" age-diagnostic information, such as index clasts, fossils, or clear-cut stratigraphic relations to deposits of unequivocal age. In order to constrain the chronostratigraphic position of the successions, an attempt to proxy-date the deposition of the conglomerates by Th-U dating of cements was undertaken. Herein, we report the first Th-U age data of calcite cements in the conglomerates of the Brandner and Gamperdona valley, respectively. Our results suggest that both successions accumulated during the Riss ice age, upon blocking of the valleys by the advance of the main valley glacier (Ill glacier). This is the first independent evidence that the alluvial successions in both valleys accumulated during the same glaciation, and the first numerical cementation age of these deposits.

2. Geographic and geologic frame

The dated successions are situated near the villages Bürs and Nenzing, Vorarlberg (Fig. 1). Each succession overlies the emergent top-to-north thrust, or thrust splay, that separates the Austroalpine tectonic domain in the south from the Flysch Zone in the north. The Austroalpine or, for that matter, the Northern Calcareous Alps (NCA), consist of stacked cover thrust nappes dominated by middle to upper Triassic neritic carbonates (Neubauer et al., 1999). During Quaternary glacial-interglacial cycles, the major valleys (Ill valley, Rhine valley) became deepened and widened, and their flanks were steepened by glacial erosion (Hantke, 1980). During glacial highstand and early retreat, in the Alpine glacial foreland and in the distal reaches of overdeepened valleys, thick successions of fluvio-lacustrine deposits accumulated. Conversely, during ice retreat and ice advance at the beginning and end of interstadials, and during early interglacials rapid, but more localized accumulation of (glacio)fluvial and glaciolacustrine deposits took place within valleys, while alluvial fans and talus aprons accumulated (Van Husen, 1983, 1999). Upon sustained interglacial conditions, however, within the Alps, linear erosion repeatedly removed much

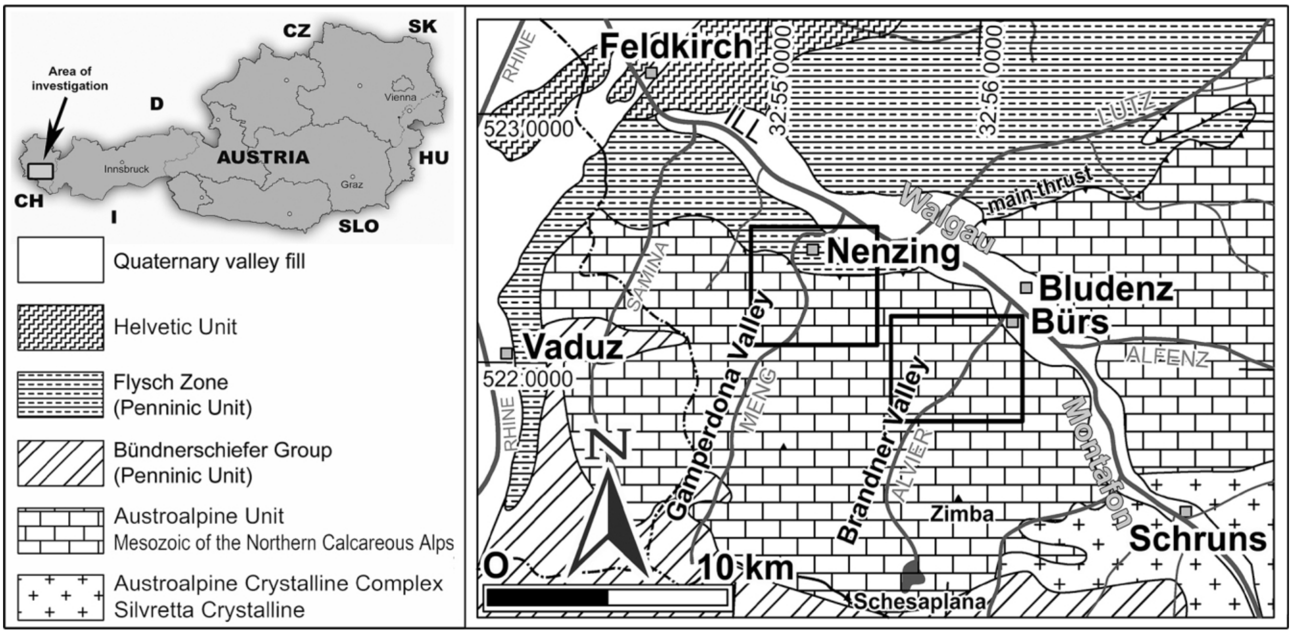

Figure 1: Left: Rectangle shows position of investigated successions in Austria. Right: Geological map of part of Vorarlberg, with major tectonostratigraphic units. Black rectangles show the map areas of figures 2 and 6. Both Gamperdona valley and Brandner valley are left-hand southern tributaries to the main valley of the river Ill. The coordinates refer to coordinate system UTM-WGS 84.

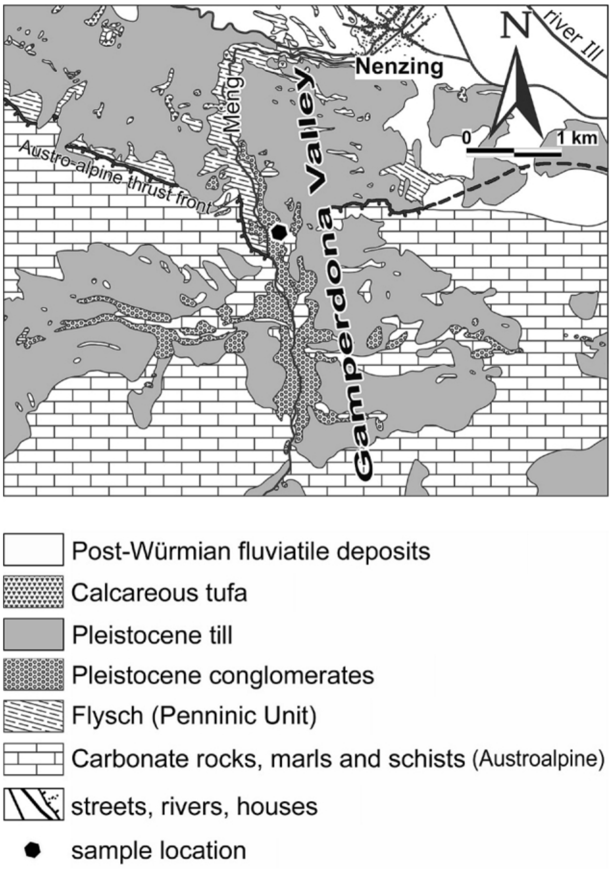

Figure 2: Geological map of lower Gamperdona valley (redrawn from Heissel et al., 1965). The conglomerate succession that originated by blocking of the valley by the Ill glacier (see text) onlaps the flanks of the valley, and is up to about 400 meters in preserved thickness. Black hexagon shows the sampling location of dated cements (coordinates of sampling location: UTM, WGS 84: zone 32 N easting 552053 northing 5224622; altitude 820 m a.s.l.).

of the sedimentary record.

Gamperdona valley, drained by the Mengbach creek, is a left-side southern tributary to the Ill valley which, in turn, debouches into the Rhine about 15 km farther to the northwest (Fig. 2). During Quaternary glaciations, the Ill glacier was one of the major, north-flowing glaciers in this part of the Alps. Along its lower reaches, overall, the Ill valley is shaped by glacial, not fluvial erosion, and the present Ill river is underfit (de Graaff, 1996, 1997). In the lower and middle reaches of the Gamperdona valley, a Quaternary succession hundreds of meters thick mainly of fluviatile conglomerates is preserved, and is incised by a deep gorge of the Mengbach (Fig. 3A). The preserved succession is up to about 400 m in thickness (Ampferer, 1908). It consists of stacked bottomset-to-topset packages, each typically a few tens of meters thick, of Gilbert-type deltas that prograded into proglacial lakes (Fig. 3B). The proglacial lakes originated from blocking of the Gamperdona valley when the Ill-valley glacier advanced and built up (de Graaff, 1996). The conglomerates consist predominantly of subrounded to very well-rounded clasts of Mesozoic carbonate rocks and, subordinately but persistently, of clasts of metamorphic rocks (Ampferer, 1908; de Graaff, 1996). The succession of conglomerates and fine-grained bottomset deposits accumulated at least before the LGM. This is indicated by overconsolidated bottomsets, localized glaciotectonic deformation and, above the succession, by basal till of the LGM and unconsolidated upper Würmian glacio-fluvial deposits (de Graaff, 1996). In the conglomerates, the clasts are densely packed, and the rocks most commonly contain a scarce matrix of lime mudstone to carbonate-lithic siltite. The succession of Gamperdona valley is intercalated by unconformities that indicate that aggradation was repeatedly interrupted by erosion (de Graaff, 1997). Based on a distinct unconformity within the succession, a lower conglomerate unit can be distinguished from an overlying upper conglomerate package, but both accumulated during the Riss glaciation; our age-dated sample is from the lower conglomerate unit (de Graaff, pers. comm., 2006). Apart from unconformities, we observed intraclasts of conglomerate a few decimeters to a few meters in size (Fig. 4). As far as the succession is accessible, the intraclasts appear to be present within discrete levels. These intraclasts suggest that the succession, or portions thereof, became readily lithified after deposition, or were transported in a frozen state. No cement fringes suited for age-dating were seen in the intraclasts. The cause, or causes, of intermittent base-level lowering, erosion and incision of unconformities is unknown. Erosion may be related to interstadial retreats of the Ill glacier, or to transient lowering of the glacier surface, or to subglacial or periglacial outbreaks of lake water. Perhaps in part because of glacial loading and compaction, openwork conglomerate fabrics with calcite cements suited for Th-U age-dating are overall quite rare (Fig. 5). The conglomerate succession of Gamperdona valley is capped by a truncation surface that, at many locations, is veneered by basal till of the Last Glacial Maximum (Ampferer, 1908; Heissel, 1960).

Brandner valley is drained by the Alvier creek, and is situated south of Gamperdona valley (Figs. 1, 6). In its lowest reaches, Brandner valley contains the Bürser Konglomerat, a fluviatile succession up to about 140 m thick of gravelly to cobbly conglomerates and, subordinately, of carbonate-lithic arenites (cf. Heissel, 1960). The succession dips very gently towards the Ill valley. The Bürser Konglomerat is underlain by a lodgement till with striated clasts of metamorphic rocks. The age of that basal till is not known; it was tentatively assigned to the Riss glacial (Heissel, 1960). Subsequently, an origin of the till during the Mindel glaciation seemed more probable (Heissel et al., 1965). Near the exit of the valley, the Bürser Konglomerat onlaps a vertical cliff of middle Triassic carbonate rocks that represented the left flank of a bedrock gorge. The Bürser Konglomerat is capped by a truncation surface that, in turn, is veneered by basal till of the Last Glacial Maximum. Today, the Bürser Konglomerat is incised by a gorge of the Alvier (Heissel, 1960; Heissel et al., 1965). In its lower part, the succession of the Bürser Konglomerat consists of gravelly to cobbly conglomerates dominated by very well- to well-rounded clasts. The clasts mainly are middle to upper Triassic neritic carbonate rocks derived from the Northern Calcareous Alps in the drainage area of the Alvier. Clasts of lower Triassic siliciclastics (Alpiner Buntsandstein), of Jurassic deep-water limestones (Adnet Group), and of metamorphic rocks are subordinate in abundance (Ampferer, 1908, Heissel, 1960). In the upper part of the succession, at an overall unchanged spectrum of clast lithologies, the clasts of sedimentary rocks are prevalently subangular to subrounded. The metamorphic rocks clasts within the Bürser Konglomerat probably are derived from erosion of the older lodgement till below the conglomerate succession (cf. Ampferer, 1908; Heissel et al., 1965). Internally, the Bürser Konglomerat is arranged in indistinct, roughly symmetrical upward-coarsening to upward-fining packages that are vertically separated by thin intervals of arenite (Heissel, 1960); the cyclic packages, however, locally are truncated and incomplete. The accumulation of the Bürser Konglomerat probably results from a rise of local base-level during glaciation. The succession may represent an aggrading braid plain that formed during advance or during retreat of the Ill glacier. Alternatively, the conglomerates accumulated in association with a glacio-lacustrine delta that, today, is preserved only in its more proximal topset portions in the lower part of Alvier valley. It is not established whether an isolated outcrop of a foreset-topset ensemble of a Gilbert-type delta at 1218 m a.s.l. far within Brandner valley pertains to the same succession as the Bürser Konglomerat; the mentioned foreset-topset package is devoid of metamorphic rock clasts, but nevertheless has been assigned by Heissel (1960, p. 45) to the Bürser Konglomerat. The Bürser Konglomerat was compared and tentatively chrono-correlated with the conglomerates in Gamperdona valley (Heissel, 1960; de Graaff, 1996). In absence of other evidence, this correlation is justified in view of the overall similar aspect (including also the clast spectrum) of both successions, and by their identical position as thick "cloggings" of valley debouches.

Figure 4: Right side of Gamperdona valley, outcrop along road. Level with intraclasts (i) of conglomerate, within a topset package of conglomerates. The identified intraclasts are a few decimeters to about 3 m in size, are identical with respect to clast spectrum, clast rounding and their fluviatile depositional setting to the conglomerates they are embedded within. Width of view about 2.5 m.

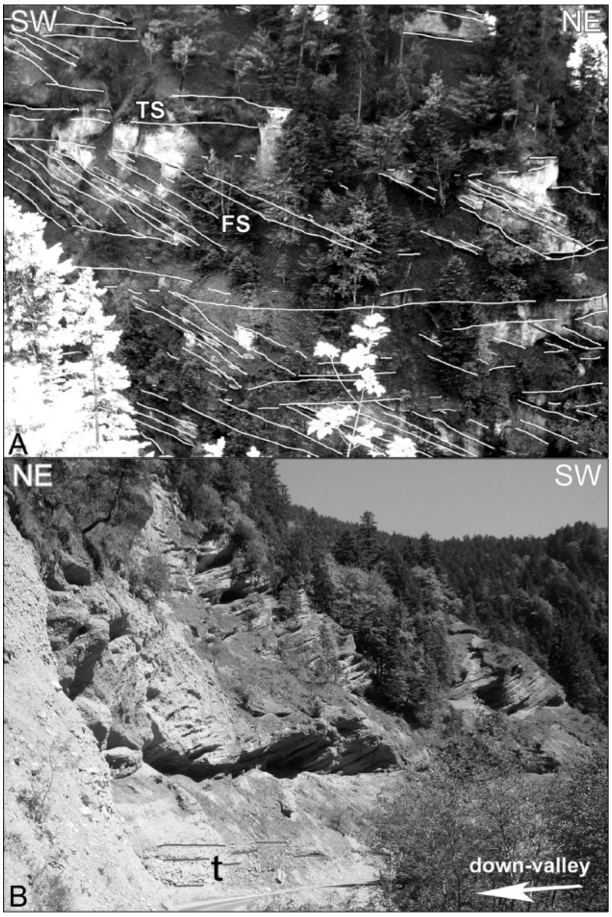

Figure 3: Succession in Gamperdona valley. A (above): View towards northwest, from sampling location onto opposite (left) gorge flank of valley. Lines highlight bedding of stacked packages of Gilbert-type deltas (FS: foresets; TS: topsets). Each package is about 10-20 m in thickness. B (below): View to south, showing part of the succession on the right side of the gorge. The section consists mainly of subhorizontal topsets (t) and inclined foresets (upper part of photo) of Gilbert-type deltas. The foresets consistently dip out valley.

3. Methods

For absolute age-dating, samples of conglomerates lithified by isopachous fringes of cement were taken in the field. The sample of Bürser Konglomerate was taken at 610 m altitude, from a huge boulder collapsed from the cliff into the gorge. The sample from Gamperdona valley was taken at about 820 m altitude, from the outcrop along the road along the right flank of the gorge. Thin sections of dated samples provided documentation of the cement. For measurements of stable isotopes of oxygen and carbon of dated cements, cleaned and polished rock slabs were excavated with a dental drill (Ø 0.3 - 1 mm). Stable isotope contents were measured on a Finnigan DeltaPlusXL mass spectrometer connected with a gas bench (Spötl & Vennemann, 2003).

For Th-U age-dating, the fringes of calcite cement were sampled with a microdrill under the microscope. Organic material was removed physically as far as possible. Samples were spiked with a mixed $^{236}U + ^{229}Th$ spike and dissolved in HNO_3, after which remaining organics were attacked with $H_2O_2 + HNO_3$. U and Th separation was done using 2 ml anion resin (Dowex™ 1x8) and HNO_3 in early series, and 0.5 ml Eichrom™ U-Teva® resin for later series. U and Th analyses were performed separately on an Nu-Instruments™ MC-ICP mass spectrometer. ^{236}U and ^{234}U

Figure 5: Sample of conglomerate of Gamperdona valley. At the sampling location (cf. Fig. 2), conglomerates contain levels of openwork fabric, and are lithified by isopachous fringes of calcite cement. Pen tip for scale.

were measured in separate electron multipliers (static mode). Thorium measurements were done in dynamic mode, by alternate measurement of ^{230}Th and ^{229}Th in the same multiplier. For thorium measurements, to control electron multiplier gain the MOSS (Be Inhouse) standard was used. For gain calibration of U, the NIST U 050 standard was taken. In our samples, the main difficulty in precise measurement of the ^{230}Th/^{232}Th ratio resulted from low ^{230}Th concentrations because of, both, low uranium content and low age versus detrital ^{232}Th contamination. For carbonates, ^{230}Th-^{234}U disequilibrium fractionation provides the basis for age-dating (Mallick, 2000). To correct for detrital contamination, the main problem in age-dating authigenic carbonates (Kaufman, 1993; Debaene, 2003), we chose the "isochron" method with several sub-samples (cf. Ludwig & Titterington, 1994; Lin et al., 1996; Frank et al., 2000; Geyh, 2001, 2005; Mallick & Frank, 2002) plotted in ^{230}Th/^{232}Th vs. ^{234}U/^{232}Th activity diagrams (Rosholt, 1976) ("Rosholt diagrams"). In the Rosholt diagrams, the plotted ^{230}Th/^{232}Th - ^{234}U/^{232}Th activity ratios of sub-samples then are connected, or approximated, by a regression line. Thus, for each calcite cement, samples were treated in sub-samples.

In general, at least three sub-samples should be measured for a regression line in the Rosholt diagram. In systems that were closed after crystallization, the precision of the age deduced by corrected activity ratios from the slope of the regression line should increase with increasing number of (sub)samples. Under diagenetic conditions, however, partial re-opening of the system is common, hence a mere increase of sub-samples not necessarily increases the precision of calculated ages. To better recognize (sub)samples that potentially were subject to re-opening, the measured contents in thorium and uranium isotopes were plotted into a "closed-system check" (CSC), i. e. into a diagram of ^{230}Th/^{238}U - ^{234}U/^{238}U activity ratios. The CSC is a semi-quantitative test of whether the system was closed or open after crystallization. In systems that are genetically related and remain closed after crystallization, except for differences in ^{230}Th/^{238}U activity ratios before closure, both the ^{230}Th/^{238}U activity ratios of (sub) samples and the ^{234}U/^{238}U ratios should cluster. In the CSC, the absolute values of activity ratios are irrelevant. The CSC is based on the confidence that within a (sub)sample set, most (sub) samples will not have been subject to re-opening. Sub-samples that suffered post-closure overprint (e. g. because of partial re-opening) plot off the cluster, hence are better recognizable. Unfortunately, up to now, no strictly quantitative method to rule out values that result from partial re-opening is available. This limitation of the method is relevant for small numbers of sub-samples, as in our case. Comparison of sub-sample plots in the CSC with the fit of sub-sample values to the regression line in the Rosholt diagrams, however, in most cases should allow to identify "problematic" sub-samples subject to overprint. Based on the comparison of the CSC with the Rosholt diagrams, thus, different Th-U ages with and without "problematic" sub-samples can be calculated. In the Rosholt diagrams, the slope of the regression line among the measured values of ^{230}Th/^{232}Th - ^{234}U/232Th activities (of sub-samples) yields corrected activity ratios; these corrected ratios are used to calculate the absolute age. For age calculation, the corrected activity ratios were fed into a Th-U disequilibrium age calculation program (Visual Basic, written by Jan Kramers, according to the equation of Kaufman & Broecker, 1965). The errors of calculated ages are indicated as 2 sigma standard deviation.

4. Cement petrography and stable isotope values

The conglomerates of both successions most commonly are densely packed and contain a scarce matrix of lime mudstone to carbonate-lithic siltite. Layers of openwork conglomerate with

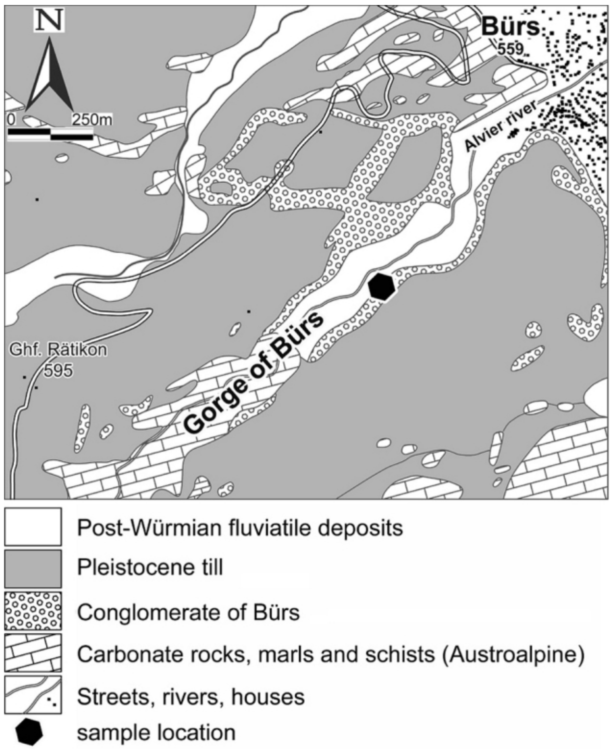

Figure 6: Geological map of lower part of Brandner valley (redrawn from Heissel et al., 1965). Black hexagon shows the sampling location of dated cements (coordinates of sampling location: UTM, WGS 84: zone 32N easting 560282 northing 5221708; altitude 610 m a.s.l.).

fringes of calcite cement are rare. In our dated samples, in clast interstitials of openwork fabrics, small geopetals of carbonate-lithic siltite to lime mudstone are locally present. These geopetals may have formed during or closely after deposition of the conglomerates, by infiltration of fine-grained clastic material into the pore space. In openwork fabrics, both the clasts and/or the mentioned geopetals may locally be overlain by a very thin fringe of micrite. More commonly, however, the dated isopachous fringes of calcite cement (Fig. 7) directly overlie the geopetals and/or the lithoclasts. The cement fringes consist of skalenohedral calcite spar. Above the cements, the remnant pore space is open.

For the sample of Bürser Konglomerat, the carbonate clasts show mean stable isotope ratios of δ13C$_{(VPDB)}$ = 0,1 ‰ and δ18O$_{(VPDB)}$ = -6,2 ‰; such values can be considered typical for lithified marine limestones and metamorphic carbonate rocks (Tab. 1) (cf. Hoefs, 1997). The stable isotopic composition of the geopetals of calcisiltite to lime mudstone termed as infiltrated matrix is characterized by a mean, each, of δ13C$_{(VPDB)}$ = 1,3 ‰ and δ18O$_{(VPDB)}$ = -10,2 ‰ at Gamperdona valley and of δ13C$_{(VPDB)}$ = 0,5 ‰ and δ18O$_{(VPDB)}$ = -11 ‰ at Bürs. At Gamperdona valley, the calcite cements show values between δ13C(VPDB) = -0,02 ‰ - to -0,94 ‰, with a mean of -0,66 ‰, and δ18O$_{(VPDB)}$ from -10,31 ‰ to -9,96 ‰, with a mean of -10,13 ‰ (Tab. 1). For the conglomerate sample of Bürs, the isotope values of calcite cements range from δ13C$_{(VPDB)}$ = -0,48 ‰ to -0,13 ‰, with a mean of -0,19 ‰, and from δ18O$_{(VPDB)}$ = -10,53 ‰ to -10,23 ‰, with a mean of -10,34 ‰ (Tab. 1). The oxygen and carbon signature of both the matrix and of the cements are typical for calcium carbonate precipitated under influence of meteoric-derived waters (Allen and Matthews, 1982; Lohmann, 1988; Hoefs, 1997). The closely similar values of both matrix and cement may result from new precipitation of very fine-grained cement during meteoric-influenced recrystallization of the matrix, and/or from dissolution of matrix followed by precipitation as a cement with crystals well-recognizable in light microscopy. Similar stable isotope values of oxygen and carbon are widespread in cements and matrices of other lithified Quaternary deposits of the Northern Calcareous Alps (Ostermann, unpubl. data).

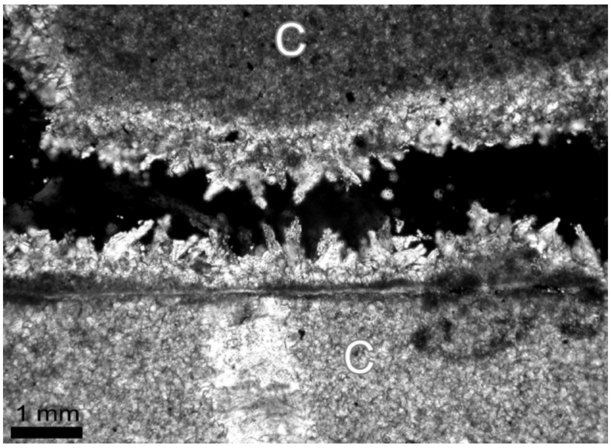

Figure 7: Thin-section photomicrograph of dated cement of Bürser Konglomerat, showing lithoclasts (c) directly overlain by a fringe of skalenohedral calcite spar. Black area is open pore space. Crossed polars.

5. Results and discussion of Th-U dating

For the calcite cement sample of the conglomerate of Gamperdona valley, the closed system check (see section Methods) shows uniform ^{234}U/^{238}U activity ratios which yields confidence that subsamples were cogenetic and remained closed systems. (Fig. 8A; see Tab. 2). The "all sub-sample values" calculation yields an age of 129.8 ± 6.5 ka b.p. (error ranges represent 2 sigma standard deviation) (Fig. 8B). In the all-data errochron (Fig. 8B), sub-sample GT1-4 and, in particular, GT1-5 plot off the regression line; hence, these two sub-samples were considered further. Re-calculating without sub-sample GT1-5 (situated farthest off the all-data regression line) results in a very close fit of all three data points to the regression line, and an age of 129 ± 6.5 ka b.p. (Fig. 8C), close to the all-data age figure. Conversely, re-calculating without sub-sample GT1-4 yields an errochron age of 201 ± 12.5 ka b.p. (Fig. 8D) which has, however, a much smaller spread. The all-sample and GT1-5 errorchrons yield identical ages within error, and we consider these to give the most probable age for the conglomerate cement.

For the samples of Bürser Konglomerat, in the closed system check the ^{234}U/^{238}U activity ratios of the sub-samples show considerable scatter, particularly for BU2-1 and BU2-2 (Fig. 9A). This means that U and Th in the samples were derived from a heterogeneous source, or the samples did not remain closed after formation. The "all sub-sample values" errorchron (Fig. 9B) has an impossibly steep slope, and no age can be determined ("no data" output, see appendix). Re-calculation without sub-samples Bu2-1 and BU2-2 yields an age of 128 ± 10 ka bp. Although the fit of the regression line in sub-sample selection 2 (Fig. 9D) is higher than in selection 1 (Fig. 9C), note that the regression line of selection 2 is based

sample	δ^{13}C [‰VPDB]	δ^{18}O [‰VPDB]	sample	δ^{13}C [‰VPDB]	δ^{18}O [‰VPDB]
GT_1_1	0.8	-10.07	BU_1_1	-0.14	-10.28
GT_1_2	0.81	-9.96	BU_1_2	-0.04	-10.35
GT_1_3	0.58	-10.09	BU_1_3	-0.18	-10.33
GT_1_4	0.94	-10.21	BU_1_4	-0.14	-10.35
GT_1_5	0.68	-10.12	BU_1_5	0.13	-10.23
GT_1_6	0.82	-10.02	BU_1_6	-0.2	-10.29
GT_1_7	0.58	-10.25	BU_1_7	-0.48	-10.41
GT_1_8	0.67	-10.05	BU_1_8	-0.48	-10.33
GT_1_9	0.75	-10.31	BU_1_9	-0.09	-10.36
GT_1_10	-0.02	-10.2	BU_1_10	-0.39	-10.53
mean	0.66	-10.13	mean	-0.19	-10.34

all values are from calcite cements

Table 1: Stable isotope values of oxygen and carbon of age-dated calcite cements of samples from Gamperdona (sampled labelled GT) and Bürs (samples labelled BU).

on three sub-samples only. For selection 1 (Fig. 9C), note that the sample pairs (BU1-3, BU1-4) and (BU1-1, BU1-2), which each have similar $^{234}U/^{238}U$ activity ratios, each also define lines parallel to the 128 ka regression line. In addition, in the closed system check (Fig. 9A), sub-sample BU_2 (that is ommitted in selection 2) plots in the center of the cluster (compare section 3. Methods above). We thus consider the solution of 128 ± 6 ka b.p. the more probable age for the cement of the Bürser Konglomerat. In summary, our Th-U ages suggest that the cementation, or a phase of cementation at least, of both the Bürser Konglomerat and of the conglomerates of Gamperdona valley is of similar age.

6. Discussion

For Gamperdona valley, the thick successions built by numerous stacked Gilbert-type deltas and proglacial lake intervals must have accumulated upon a marked, net rise of local base-level; this, in turn, seems hardly compatible with interglacial conditions. In the present context, the pertinent rise of base-level most probably was caused by the Ill-valley glacier (de Graaff, 1996, 1997). This implies that the Ill glacier nourished by a large drainage area advanced far off the local glaciers fed by smaller drainage areas of the tributary valleys (Fig. 10A, 10B). Similar situations, with glaciers of major valleys advancing far ahead local glaciers, occurred during the beginning of the LGM in more eastern parts of the NCA (e. g. Ziller glacier, Inn glacier; Hantke, 1980; Poscher, 1993; van Husen, 1999; Wischounig, 2006). Only during pleniglacial conditions, the entire succession became buried (Fig. 10C). As mentioned in section 2, our dated sample from the succession of Gamperdona valley pertains to the lower conglomerate unit that is spearated by an unconformity from the overlying upper conlgomerate unit. The cementation age thus provides a minimum age for this lower unit only. Aside of the unconformity that separates the lower from the upper conglomerate unit, the intraclasts of conglomerates also record intermittent periods of erosion. At present, however, it is not known whether the intraclasts represent vestiges of conglomerates of significantly larger age or whether they are penecontemporaneous with the succession they are embedded within. By their overall characteristics (clast size range, composition, rounding, etc.), the intraclasts are not obviously different from their host conglomerates. For the Bürser Konglomerat, taking the cementation age of 128 ± 10 ka bp., a possible interpretation is that also this succession accumulated during buildup of the Ill glacier, and became subsequently cemented. The preservation of the succession precludes to assess the potential relation of the Bürser Konglomerat to the Ill glacier with more certainty. Our

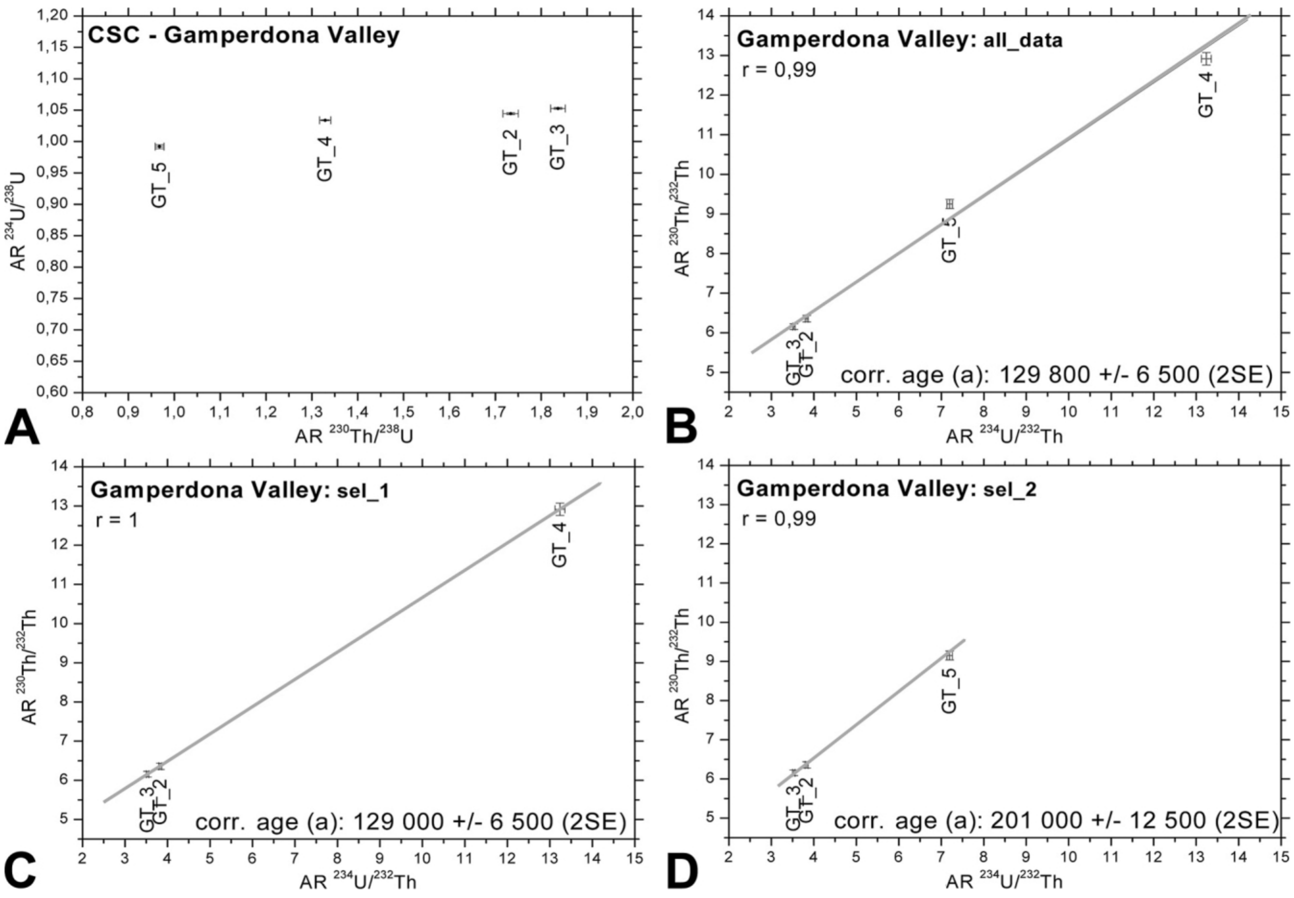

Figure 8: A: Diagram of activity ratios of $^{230}Th/^{238}U$ versus $^{234}U/^{238}U$ ("closed-system check", CSC) for sample of Gamperdona valley. B: "All-data" regression line and calculated age. Note that in the CSC and on the all-data regression line, sub-sample GT1-5 plots farthest off. C: Regression without sub-sample GT1-5. Note that the calculated age is close to the age as deduced for the all-data case. D: Regression and calculated age without sub-sample GT1-4, but including GT1-5. Note that in this choice, the calculated age is distinctly higher. The error range of calculated ages is 2 SE = 2 sigma standard error. AR = activity ratio; r = Pearson´s correlation coefficent. See text for discussion.

Sample	U [ppb]	Th [ppb]	($^{234}U/^{238}U$)	($^{230}Th/^{232}Th$)	($^{230}Th/^{234}U$)
GT_1	574.0 ± 1.0	472.3 ± 4.3	1.044 ± 0.001	6.359 ± 0.083	1.660 ± 0.016
GT_2	539.6 ± 0.9	nd[a]	1.052 ± 0.001	nd[a]	nd[a]
GT_3	580.8 ± 1.0	522.9 ± 4.1	1.053 ± 0.001	6.157 ± 0.071	1.745 ± 0.015
GT_4	434.8 ± 1.0	98.3 ± 0.8	0.992 ± 0.003	12.918 ± 0.159	0.976 ± 0.010
GT_5	1261.6 ± 2.2	547.0 ± 4.7	1.034 ± 0.001	9.251 ± 0.116	1.285 ± 0.012
BU_1	408,3 ± 0.7	695.3 ± 16.5	1.091 ± 0.001	3.048 ± 0.077	1.576 ± 0.014
BU_2	306.1 ± 0.5	424.3 ± 3.4	1.136 ± 0.001	3.652 ± 0.044	1.476 ± 0.014
BU_3	495.7 ± 0.9	1230.4 ± 10.1	1.218 ± 0.001	2.067 ± 0.026	1.396 ± 0.014
BU_4	459.2 ± 0.8	379.0 ± 2.9	1.098 ± 0.001	6.454 ± 0.074	1.608 ± 0.014
BU_5	494.9 ± 0.9	698.8 ± 5.1	1.192 ± 0.001	3.332 ± 0.036	1.308 ± 0.011
BU_6	401.2 ± 0.7	620.7 ± 5.3	1.188 ± 0.001	3.232 ± 0.043	1.394 ± 0.014

All ratios are activity ratios. Propagated in-run errors are 2σ standard errors. All isotope ratios are raw uncorrected values.
[a]nd: no data - 230Th analyse was not determined because of an error

Table 2: U-series isotope activtiy ratios and U-series ages for age-dated cements samples from Gamperdona valley (samples labelled GT) and from Bürs (samples labelled BU).

age data imply that at least the lower, V-shaped parts of Alvier and Gamperdona valley, respectively, that today are onlapped by the conglomerate successions were largely shaped prior to the Riss Glacial. This fits with observations made in other parts of the Alps, where sedimentary fills of gorges indicate that most of the gorge landform is of pre-Würmian age (Tricart, 1960; Hantke, 1980; Wischounig, 2006).

For the time of about 130 ka b.p., the probable cementation age of the conglomerates, both SPECMAP (Imbrie et al., 1984) and speleothems from Soreq cave (Ayalon et al., 2002; Bar-Matthews

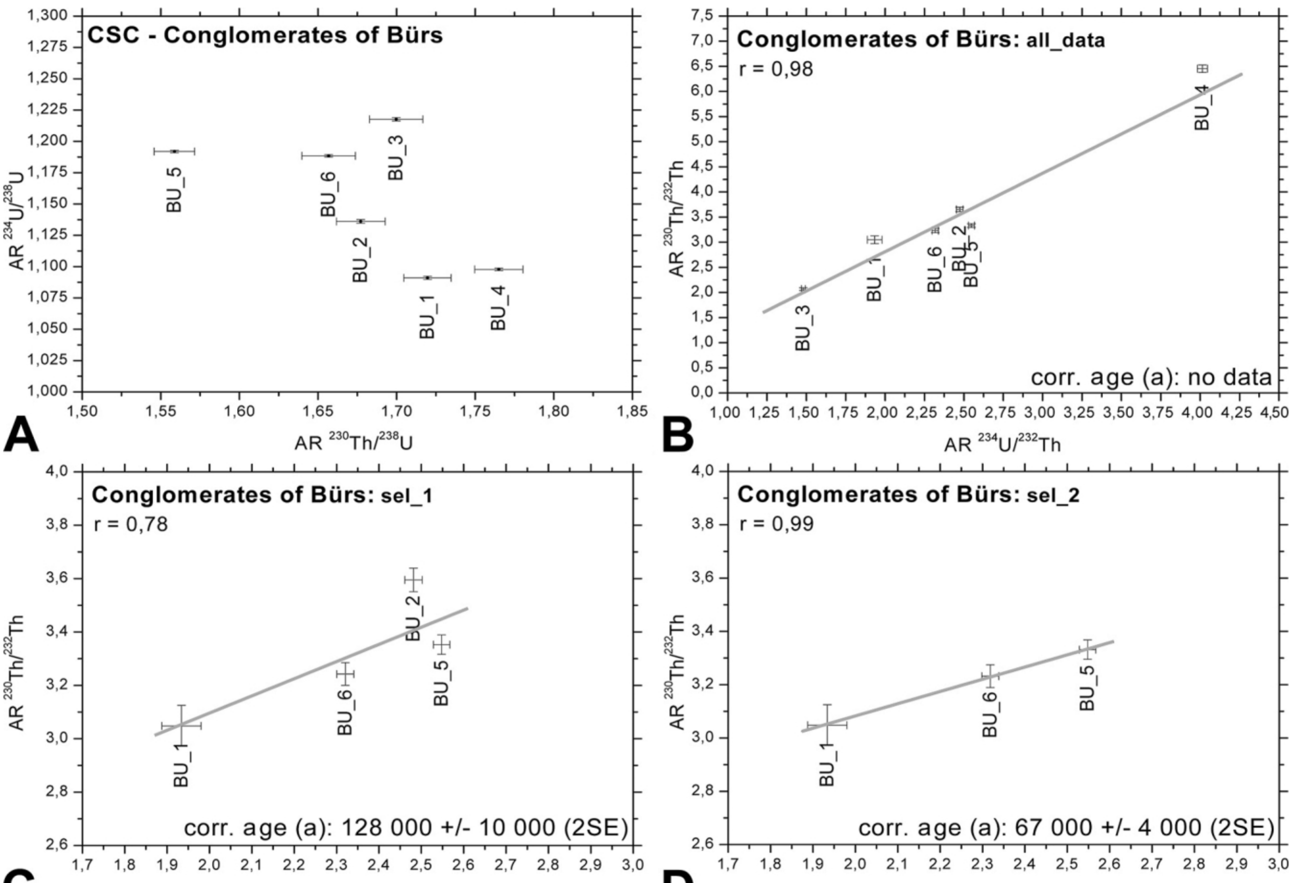

Figure 9: A: Diagram of activity ratios of $^{230}Th/^{238}U$ versus $^{234}U/^{238}U$ ("closed-system check", CSC) for sample of Bürs conglomerate. B: "All-data" regression. For the all-data case, the calculation yields no mathematically meaningful result ("no data" output). C: Regression and calculated age without sub-samples BU2-1 and BU 2-2. Note that in this regression, sub-sample BU1-2 plots farthest off. D: Isochron regression line and calculated age without sub-samples BU1-2, BU2-1 BU2-2. The error range of calculated ages is 2 SE = 2 sigma standard error. AR = activity ratio; r = Pearson´s correlation coefficent. See text for discussion.

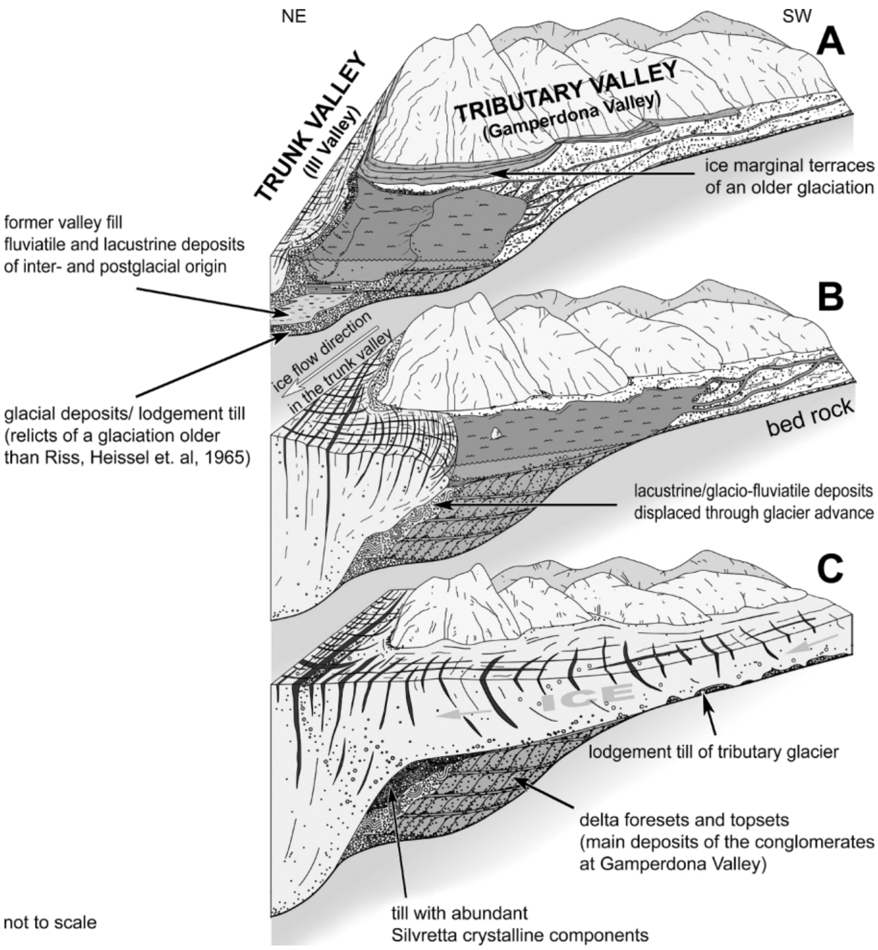

Figure 10: Depositional model of proglacial succession (modified from de Graaff, 1996). A: Tributary valleys became progressively blocked during advance of the Ill glacier. Accumulation of proglacial lacustrine and alluvial successions started in the lower reaches of tributary valleys. B: Build-up of the main-valley glacier. Deposition of proglacial successions continued. Their marginal parts became involved in soft-sediment deformation by glacial loading. C: During pleniglacial conditions, the entire succession was buried by ice. During lithification of the conglomerates, similar conditions than shown in A may have pertained.

& Ayalon, 1997; Bar-Matthews et al., 2000) indicate the beginning of the Riss-Würm interglacial (Fig. 11). Conversely, for the same time, speleothems of Devils Hole (Winograd et al., 1992) record peak interglacial conditions (Fig. 11). Within the Alps, only a few comparative data from a similar age range are available. For speleothems of Spannagel cave (Zillertal Alps, 2200-2500 m a.s.l.) 145 km east of Bürs and Gamperdona, Holzkämper et al. (2005) determined that their growth re-commenced at about 137 ka b.p.; this was interpreted as the start of the Riss-Würm Interglacial (Eemian). Because of a comparatively low resolution of the isotope record, however, a more detailed identification of palaeoclimatic variations during the early Eemian was not possible (Holzkämper et al., 2005). For speleothems of Blasloch cave (690 m a.s.l.), 425 km towards the east of the locations described herein, Offenbecher (2004) identified three phases of growth (139-133 ka, 128-117, 121-115 ka b.p.; error ranges of ages 7.5-5 ka). For the earliest Eemian, between about 135 ka and 128 ka, no speleotheme growth is indicated at Blasloch (Offenbecher, 2004). Within the growth interval from 128 - 120 ka b. p., $\delta 18O_{(VPBD)}$ peaks of about -10 ‰ are present three times, marking "significant" cooling events (Offenbecher, 2004).

The evidence in summary suggests that the age-dated cements of the investigated conglomerates precipitated during termination of the Riss glacial to the earliest Eemian. On the other hand, if there existed a significant lag between melting of the Ill glacier and cementation, the unlithified gravelly sediments that clogged the side valleys most probably had been eroded within a short interval of time. We infer that the precipitation of cements took place during deglaciation, when the tributary valleys still were blocked by ice, or dead ice, in the trunk valley. Cement precipitation during early deglaciation may have been favoured by exposure of large areas of glacial till, leading to meteoric groundwaters waters of relatively high content in dissolved calcium carbonate. Thorium-uranium age data mainly from Quaternary lithified talus and pebbly alluvium of the Northern Calcareous Alps indicate that cement precipitation in many cases took place closely after deposition. In other cases, however, a distinct lag between deposition and cementation is indicated. No straightforward correlation, however, can be established between the type of depositional system and "lagged cementation", and discrete phases of cement precipitation can be distinguished in some cases (Ostermann, unpubl. data). Our data show that even with some potential lag of cementation relative to deposition, thorium-uranium age-dating of cements provides valuable constraints for the reconstruction of geological history.

6. Conclusions

1. Th-U ages of calcite cements of Bürser Konglomerat and of a thick conglomerate succession in Gamperdona valley suggest that both successions accumulated during the Riss Glacial, during blocking of the valleys in association with advance of the Ill glacier.
2. At least the lower, V-shaped reaches of both the Alvier valley (Bürser Konglomerat) and Gamperdona valley, onlapped by the conglomerate successions, were largely shaped before the Riss glaciation.
3. The gorges incised into both successions of conglomerates may have been cut, in part at least, during the Riss-Würm interglacial, and became further shaped mainly during the Late-Glacial to Holocene.

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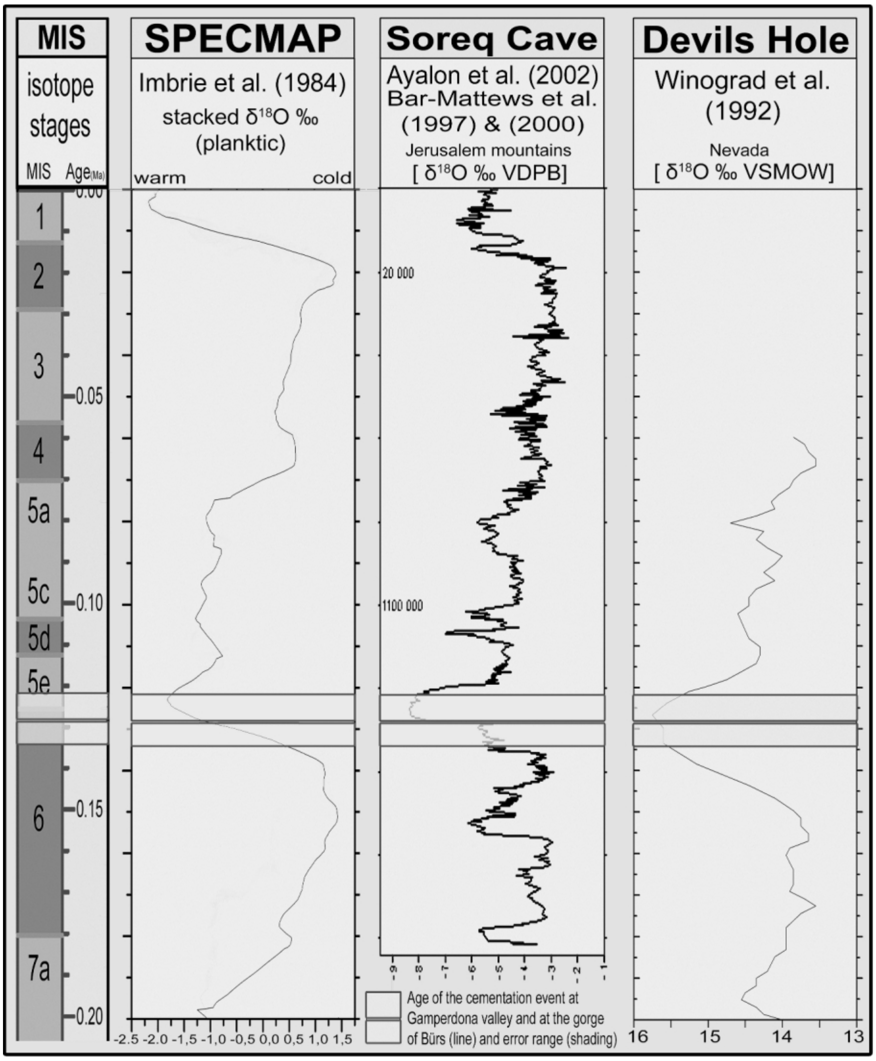

Figure 11: Comparison of conglomerate cementation age with different palaeoclimate records provided by oxygen isotopes. See text for discussion.

References

Allan, J.R. and Matthews, R.K., 1982. Isotope signatures associated with early meteoric diagenesis. Sedimentology, 29, 797-817.

Ampferer, O., 1908. Glazialgeologische Beobachtungen in der Umgebung von Bludenz. Jahrbuch der kaiserlich-königlichen geologischen Reichsanstalt, 58, 627-636.

Ayalon, A., Bar-Matthews, M. and Kaufman, A., 2002. Climatic conditions during marine isotopic stage 6 in the Eastern Mediterranean region, as evident from the isotopic composition of speleothems; Soreq Cave, Israel. Geology, 30, 303-306.

Bar-Matthews, M. and Ayalon A., 1997. Late Quaternary Paleoclimate in the Eastern Mediterranean Region from Stable Isotope Analysis of Speleothems at Soreq Cave, Israel. Quaternary Research, 47, 155-168.

Bar-Matthews, M., Ayalon, A. and Kaufman, A., 2000. Timing and hydrological conditions of Sapropel events in the Eastern Mediterranean, as evident from speleothems, Soreq Cave, Israel. Chemical Geology, 169, 145-156.

Debaene, G., 2003. Uranium-series dating of marly sediments: applications to Jaroszów fossil lake (SW Poland). Geochronometria, 22, 15-26.

de Graaff, L. W. S., 1996. The fluvial factor in the evolution of alpine valleys and of ice-marginal topography in Vorarlberg (W-Austria) during the upper Pleistocene and Holocene. Z. Geomorph. N. F., suppl. 104, 129-159.

de Graaff, L.W.S., 1997. Der fluviale Faktor bei der Entwicklung alpiner Täler und der Eisrand-Topographie in Vorarlberg (Westösterreich) während des oberen Pleistozäns und Holozäns. Jahrbuch des Vorarlberger Landesmuseumvereins, 1997, 21-53.

Frank, N., Braum, M., Hambach, U., Mangini, A. and Wagner, G., 2000. Warm period growth of travertine during the last interglaciation in Southern Germany. Quaternary Research, 54, 38-48.

Frisch, W., Székely, B., Kuhlemann, J. and Dunkl, I., 2000. Geomorphological evolution of the Eastern Alps in response to Miocene tectonics. Zeitschrift für Geomorphologie, Neue Folge, 44, 103-138.

Geyh, M.A., 2001. Refections on the $^{230}Th/^{234}U$ dating of dirty material. Geochronometria, 20, 9-14.

Geyh, M.A., 2005. Handbuch der physikalischen und chemischen Altersbestimmung. Wissenschaftliche Buchgesellschaft, Darmstadt, 211 pp.

Hantke, R., 1970. Zur Datierung spätwürmzeitlicher Gletscherstände am Rande des Säntisgebirges. Eclogae geologicae Helvetiae, 63, 2, 279-291.

Hantke, R., 1980. Eiszeitalter - Die jüngste Erdgeschichte der Schweiz und ihrer Nachbargebiete - Letzte Warmzeiten, Würm-Eiszeit, Eisabbau und Nacheiszeit der Alpen-Nordseite vom Rhein- zum Rhone-System. Ott Verlag, Thun, 703 pp.

Heissel, G., 1960. Das Konglomerat von Bürs bei Bludenz (Vorarlberg). Jahrbuch des Vorarlberger Landesmuseumvereins, 1960, 44-49.

Heissel, W., Oberhauser, R., Reithofer, O. and Schmidegg, O., 1965. Geologische Karte des Rätikon 1/25.000. Geologische Bundesanstalt Wien.

Hoefs, J., 1997. Stable Isotope Geochemistry. Springer, Berlin, 201 pp.

Holzkämper, S., Spötl, C. and Mangini, A., 2005. High-precision constraints on timing of Alpine warm periods during the middle to late Pleistocene using speleothem growth periods. Earth and Planetary Science Letters, 236, 751-764.

Imbrie, J., Hays, J.D., McIntyre, A., Mix, A.C., Morley, J.J., Pisias, N.G., Prell, W.L. and Shackleton, N.J., 1984. The orbital theory of Pleistocene climate: support from a revised chronology of the marine $\delta^{18}O$ record. In: A. Berger, J. Imbrie, J. Hays, G. J. Kukla and E. Saltzman (eds.), Milankovitch and Climate. Reidel, Dordrecht, pp. 269–305.

Kaufman, A., 1993. An evaluation of several methods for determining $^{230}Th/^{234}U$ ages in impure carbonates. Geochimica et Cosmochimica Acta, 57, 2303-2317.

Kaufman A., and Broecker W.S., 1965. Comparison of ^{230}Th and ^{14}C ages for carbonate materials from lakes Lahontan and Bonneville. Journal of Geophysical Research, 70, 4039-4054.

Lin, J.C., Broecker, W.S., Anderson, R.F., Hemming, S., Rubenstone, J.L. and Bonani, G., 1996. New $^{230}Th/^{234}U$ and ^{14}C ages from Lake Lahontan carbonates, Nevada, USA, and a discussion of the origin of initial thorium. Geochimica Cosmochimica Acta 60, 2817–2832.

Lohmann, K.C., 1988. Geochemical patterns of meteoric diagenetic systems and their applications to studies of paleokarst. In: N.P. James and P.W. Choquette (eds.), Paleokarst. Springer, New York, pp. 58-80.

Ludwig, K.R. and Titterington, D.M., 1994. Calculation of $^{230}Th/^{234}U$ isochrons, ages, and errors. Geochimica et Cosmochimica Acta, 58, 5031-5042.

Mallick, R., 2000. Entwicklung einer Mikrobeprobung zur Th/U-Datierung und Anwendung an quartären Travertinen aus dem Thüringer Becken. Unpubl. Ph.D. Thesis, Ruprecht-Karls-Universität Heidelberg, 173 pp.

Mallick, R. and Frank, N., 2002. A new technique for precise uranium-series dating of travertine micro-samples. Geochimica et Cosmochimica Acta, 66, 4261-4272.

Neubauer, F., Genser, J. and Handler, R., 1999. The Eastern Alps: Result of a two-stage collision process. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92, 117-134.

Offenbecher, K.-H., 2004. Stabile Isotope in Stalagmiten als Indikatoren der Klimaentwicklung im Quartär der österreichischen Alpen. Unpublished Ph. D. Thesis, University of Innsbruck, 233 pp.

Ortner, H. and Stingl, V., 2001. Facies and basin development of the Oligocene in the Lower Inn Valley, Tyrol/Bavaria. In: W.E. Piller and M.W. Rasser (eds.), Paleogene of the Eastern Alps. Österreichische Akademie der Wissenschaften, Schriftenreihe der Erdwissenschaftlichen Kommission, 14, pp. 153-196.

Poscher, G., 1993. Neuergebnisse der Quartärforschung in Tirol. In: Geologie der Oberinntaler Raumes, Schwerpunkt Blatt 144 Landeck. Arbeitstagung der Geologischen Bundesanstalt, pp. 7-27.

Rosholt, N., 1976. $^{230}Th/^{234}U$ dating of travertines and caliche rinds. Geological Society of America, Abstracts with Programs, 8, 1079.

Spötl, C. and Vennemann, T., 2003. Continuous-flow isotope ratio mass spectrometric analysis of carbonate minerals. Rapid Communications in Mass Spectrometry, 17, 1004-1006.

Summerfield, M.A., 1991. Global Geomorphology. Longman Scientific & Technical, Essex, 537 pp.

Tricart, J., 1960. A subglacial gorge: La gorge du Guil (Hautes Alpes). Journal of Glaciology, 3, 646-651.

Van Husen, D., 1983. General sediment development in relation to the climatic changes during Würm in the eastern Alps. In: E.B. Evenson, Ch. Schlüchter and J. Rabassa (eds.), Tills and Related Deposits. Balkema, Rotterdam, pp. 345-349.

Van Husen, D., 1999. Geological Processes during the Quaternary. Mitteilungen der Österreichischen Geologischen Gesellschaft, 92, 135-156.

Winograd, I.J., Coplen, T.B., Landwehr, J.M., Riggs, A.C., Ludwig, K.R., Szabo, B.J., Kolesar, P.T. and Revesz, K.M., 1992. Continuous 500,000-year climate record from vein calcite in Devils Hole, Nevada. Science, 258, 255-260.

Wischounig, L., 2006. Das Quartär bei Steinberg am Rofan (Tirol): Stratigraphie, Sedimentologie und Aspekte der Landschaftsentwicklung. Unpubl. M. S. thesis, University of Innsbruck, 105 pp.

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